BIOENGINEERED
2023, VOL. 14, NO. 1, 2244754
https://doi.org/10.1080/21655979.2023.2244754

Microplastics as an emerging contaminant of concern to our environment: a brief overview of the sources and implications

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ABSTRACT

Over the years, it has become evident that microplastics are one of the most important contaminants of concern requiring significant attention. The large abundance of microplastics that are currently in the environment poses potential toxicity risks to all organisms that are exposed to them. Microplastics have been found to affect the physiological and biological processes in marine and terrestrial organisms. As well as being a contaminant of concern in itself, microplastics also have the ability to act as vectors for other contaminants. The potential for microplastics to carry pollutants and transfer them to other organisms has been documented in the literature. Microplastics have also been linked to hosting antibiotic resistant bacteria and antibiotic resistance genes which poses a significant risk to the current health system. There has been a significant increase in research published surrounding the topic of microplastics over the last 5 years. As such, it is difficult to determine and find up to date and relevant information. This overview paper aims to provide a snapshot of the current and emerging sources of microplastics, how microplastics can act as a contaminant and have toxic effects on a range of organisms and also be a vector for a large variety of other contaminants of concern. The aim of this paper is to act as a tool for future research to reference relevant and recent literature in this field.

ARTICLE HISTORY
Received 29 May 2023
Revised 29 July 2023
Accepted 1 August 2023

KEYWORDS
Microplastics; contaminants of emerging concern; adsorption; ecotoxicity; pollution

1. Introduction

The production of plastic has increased exponentially since the 1950s, leading to approximately 359 million tons of virgin plastic being produced per year [1]. The rise of using plastic materials in everyday life has unintentionally led to the emergence of a contaminant that poses a serious concern to our environment. Microplastics are fragmented plastic pieces that are less than 5 mm in length, and due to their size, once they have been polluted into the environment, they are difficult to remove. Microplastics have been discovered in all corners of the globe, from Antarctica [2] to deserts [3]. The abundance of microplastics in the environment is significant and effect of the pollutant has become a topic of interest in the current literature.

Public concern over microplastic pollution has risen significantly over the years. Microplastics have the potential not only to be a toxic pollutant but also carry other contaminants of concern and transport them through the environment. Microplastics have been found to affect ingestion rates and feeding capacity in marine life [4,5], and also stunt and inhibit the growth of roots and leaves in plants [6,7]. Microplastics contaminated with fluoranthene have also been seen to transfer the pollutant from microplastic to a host organism [8]. The full extent of issues associated with microplastics are still unknown but through recent studies, it is apparent that microplastics should be classed as a significant contaminant of concern.

The popularity of researching microplastics has increased significantly over the last five years (Figure 1). With large volumes of knowledge about microplastics currently available, it is easy to become overwhelmed and it has become difficult to discover what information is relevant and up to date. The purpose of this overview paper is to summarize key aspects relating to the implications of microplastics as an emerging contaminant of concern. An insight into how microplastics are

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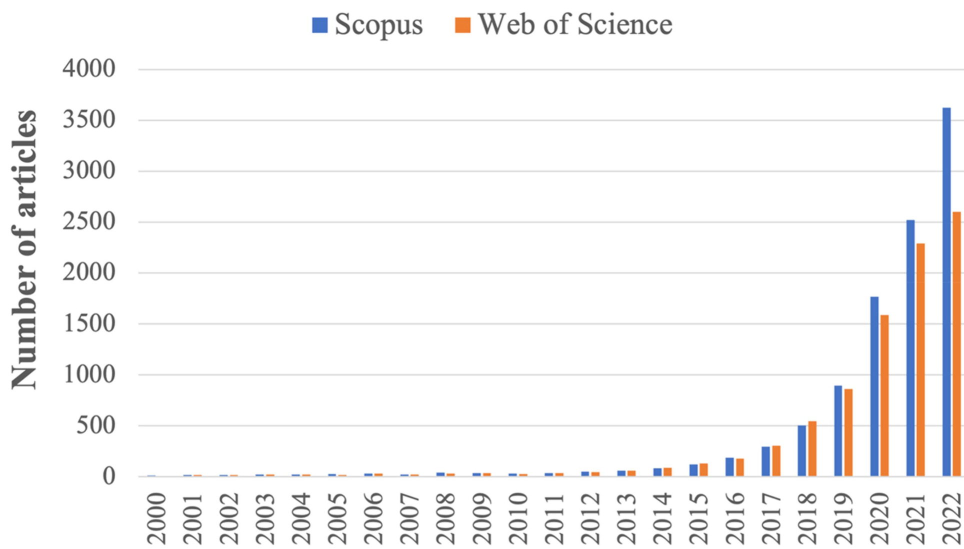

Figure 1. Number or articles on scopus and web of science based on the search of the words 'microplastic' or 'micro-plastic'.

not only a contaminant of concern in themselves but also have the potential to be a vector for other emerging contaminants will be discussed. Known and emerging sources of microplastics will be studied and future research areas will be recommended based on the findings of this brief overview.

2. Sources of microplastic pollution

Sources of microplastic pollution can be categorized into two sub-categories: pollution caused by primary microplastics and pollution caused by secondary microplastics [9]. Primary microplastics are those that were manufactured already in the microplastics (<5 mm) size range, for example, pellets, nurdles, or fibers. Secondary microplastics are classified as plastics that have originated from plastics in the macro range (>5 mm). The full extent of all sources of secondary microplastics are still unknown, however common sources include the fragmentation of microplastics caused by weathering or abrasive forces and the generation of microplastics from tires on our roads [10].

With microplastics becoming an increasing topic of interest, source identification varies depending upon the literature in question. For example, research papers exploring the occurrence of microplastics in oceans or river systems may stipulate that the major source of microplastic pollution is from stormwater runoff and sewer discharge [11]. Although this is an important identification of the pathway in which microplastic pollution can travel, it is not the original source of the pollution. Wastewater treatment plants are known to act as a funnel for microplastic pollution [12], but how the microplastics end up using this pathway is still not entirely known. Determining original sources of microplastic pollution has become an important field in the current literature. Outlined in this section and illustrated in Figure 2 are the commonly known and emerging sources of microplastic pollution.

2.1. Macroplastic fragmentation

The reduction of macroplastics into microplastics is one of the most common sources of microplastic pollution in the environment. In 2018, an estimated 4% of the plastic that was produced entered the environment as pollution [13]. Although plastics can take hundreds of years to completely degrade in the natural environment [14], fragmentation from macro size plastics in to the micro size range occurs throughout the entire degradation process. Plastics fragmentation is caused by the exposure to chemical (photodegradation, thermo-oxidative degradation, hydrolytic degradation), physical (abrasive forces) and biological stressors [15]. A substantial amount of microplastic

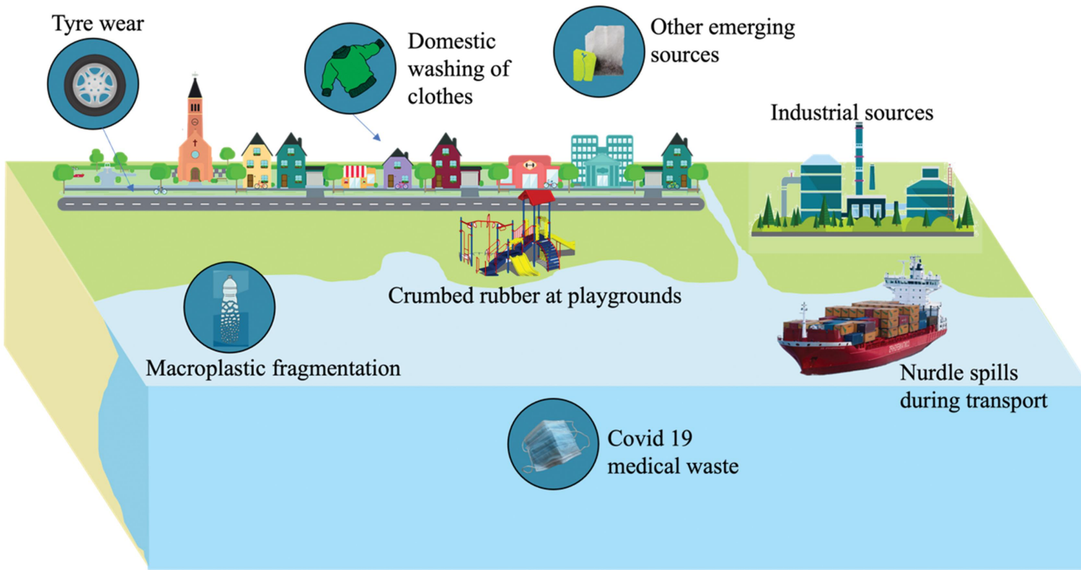

Figure 2. Common and emerging sources of microplastic pollution.

pollution that is generated through fragmentation comes from the physical stressors applied to automotive tires [16]. Through appropriate management of plastic pollution, a reduction in secondary microplastics being released into the environment can be seen.

2.2 Nurdle spills

Nurdles (plastic pellets) are the precursor to all plastics products that have ever been manufactured. As such, nurdles are shipped for further processing all around the globe. In recent years, citizen science programs (AUSMap, The Great Nurdle Hunt, Nurdle Patrol), have discovered a high abundance of nurdles washing up on coastlines across all continents (Figure 3).

In 2016, it was estimated that 230,000 tons of nurdles were entering the environment on an annual basis [18]. Nurdles can enter the environment through a range of pathways, with a common pathway being the unintentional release from cargo ships. In 2021, Sri Lanka saw approximately 1,680 tons of nurdles spill into their oceans after a cargo ship caught fire [19]. Similarly, in 2017, a cargo ship off South Africa was hit by a storm and lost two shipping containers that were transporting nurdles [20]. Although not intentional, nurdle spills have become a significant source of microplastic pollution into the environment.

2.3 Textile washing

With the introduction of synthetic fibers into the textile industry came the unintentional release of microplastic pollutants into the environment [21]. Microplastics are predominantly generated during the production of the textile material and during the domestic washing of the material. In 2011, a study investigating the microplastics generated during the domestic washing of a singular polyester garment found it generated more than 1900 microplastic fibers per wash [22]. Study's considering factors that increase microplastic fiber generation rates found detergent to increase the generation of polyester microfibres by more than 75% [23]. Microplastics generated through domestic washing ends up in wastewater treatment plants which were not specifically designed to tackle this emerging contaminant [24]. As this source of microplastic pollution cannot be feasibly removed, remediation methods for reducing the environmental impact are currently being studied within the literature. Reduction in environmental loading of microplastics from textiles has been seen through the physical remediation strategies of attaching filters to washing machines [25,26], and through chemical modifications applied during the production of the synthetic textile [27].

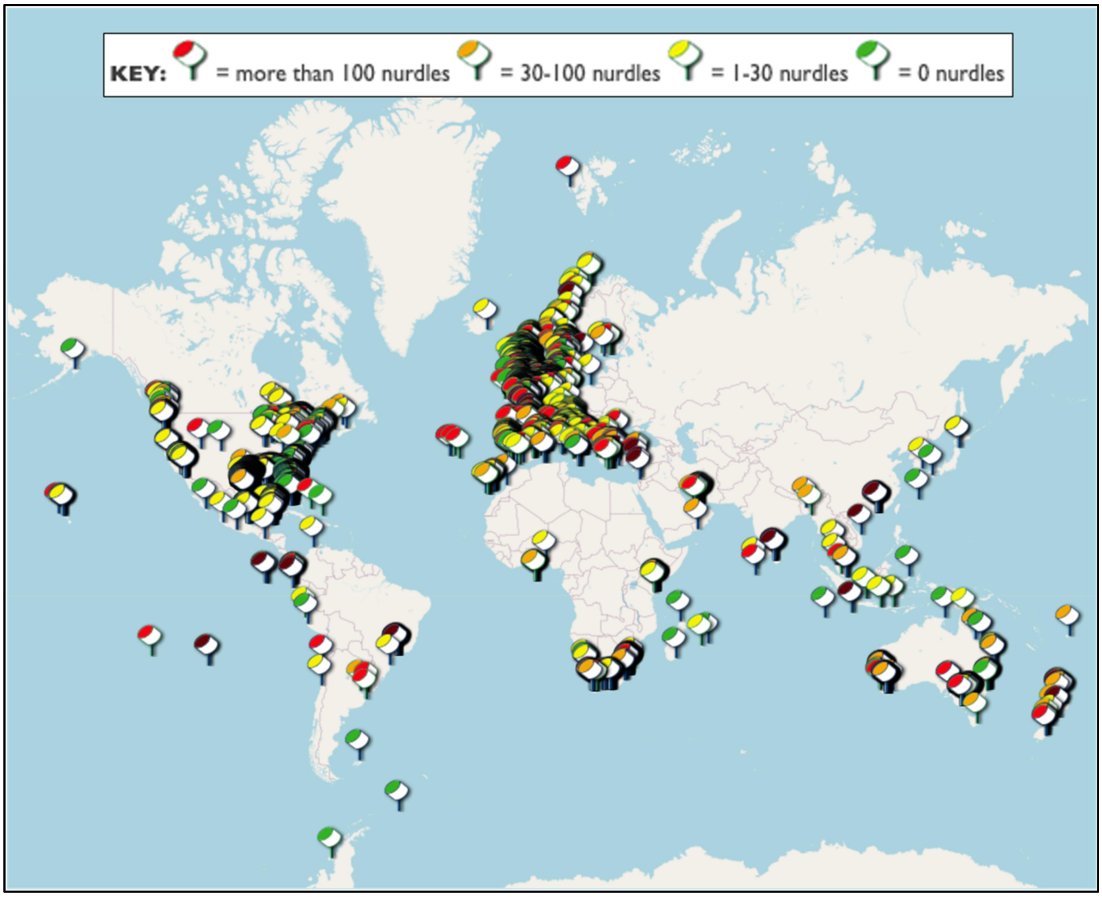

Figure 3. Locations where nurdles have been discovered on coastline. Research led by the international citizen science program 'The Great Nurdle Hunt' [17].

2.4. Emerging sources

Understanding and investigating all sources of microplastic pollution is important to mitigating the emerging issues and concerns that microplastics are associated with. Alongside the previously mentioned sources of microplastic pollution, that are well documented in the literature, comes emerging sources that require immediate attention to reduce its environmental impact.

2.4.1. Tea bags

In the past couple of years, an unexpected source of microplastic pollution has come from one of the most popular beverages in the world – tea. The use of plastic materials in the construction of tea bags is to enhance the integrity of the bag when submerged in liquid. Limited literature is available on the generation of microplastics during the brewing of tea using synthetic materials, however initial studies have shown that microplastics are being generated and at significant volumes. A study by Hernandez et al. [28] stated that 11.6 billion microplastics and 3.1 billion nano plastics are generated in a single cup of tea brewed with nylon and PET tea bags. Afrin et al. [29] also studied the release of microplastics from bagged tea, however only found there to be 504 particles per cup. Given that the differences in reporting are quite significant, the generation rates are currently inconclusive but it is apparent that tea bags do in fact release microplastics.

2.4.2. Plastic recycling facilities

Although plastic recycling facilities are on the forefront of reducing the overall impact of overuse of plastic materials, they have recently been spotlighted as a potentially large polluter of microplastics into our environment. When the plastic waste enters a recycling facility, it is reduced in size through the process of shredding [30]. Due to its mechanical nature of the shredder, it is expected to generate plastic particles smaller than necessary. After the shredding process, the plastic waste material is then washed to remove any contaminants such as food waste or adhesives [31]. It is in this process where microplastics may unintentionally be left in the wastewater and pollute the environment. Research into this field has only just begun, with initial findings confirming the occurrence of microplastics being linked to plastic recycling facilities [32,33]. Further research into factors that affect generation rates and environmental loading amounts are still required to determine the significance of the source as a microplastic polluter.

2.4.3. Crumbed rubber in playgrounds

End-of-life tires have been a material that has overwhelmed the waste management industry with countless issues, from illegal stockpiling to difficulties in landfilling. Over the years, there have been numerous attempts to deal with the material, but currently, there is no perfect solution [34]. The transformation of end-of-life tires into a reusable product has always been the goal. One of these inventions was recycling tires into rubber crumb that can be used as the softfall surfaces for playground equipment. However, an unintentional downside to this recycling solution has found the rubber crumb softfall to be a source of microplastic pollution [35]. AUSMAP, a globally recognized citizen science program in Australia, worked in collaboration with ReefClean to investigate rubber crumb loss from playgrounds in the Great Barrier Reef catchment [36]. The report discovered approximately 1.2 million rubber crumbs were released from the playgrounds in the catchment area. Crumbed rubber for playground use was once seen as a great waste management strategy for end-of-life tires, however due to the unintentional release of microplastics, it has now been found to be a new material of environmental concern.

2.4.4. Covid-19 medical waste

During the COVID-19 pandemic there was a significant increase in the use of personal protective equipment (PPE) to reduce the spread of infection. To keep costs down, most of the PPE used in a hospital setting is made of a plastic, typically polypropylene (PP) [37]. With the significant increase in single-use plastic PPE, comes the potential consequence of improper disposal. Recent studies have suggested that COVID-19 medical waste has a high probability of becoming a significant source of microplastic pollution in our environment [38,39]. As we are still in the tail end of the pandemic, it is important to focus on this area of study and ensure that we appropriately manage the waste produced from the COVID-19 pandemic.

3. Microplastics as a contaminant of concern

Microplastic pollution has been documented in terrestrial, aquatic, and atmospheric environments [40–42]. The trophic transfer of microplastics in the aquatic food chain [43] has unavoidably seen the exposure of microplastics in the human body [44]. The spread of microplastics through nature is significant, and the effect that microplastic contamination has on humans, flora, and fauna is a particular focus of the current literature.

3.1 Effect of microplastics on humans

Due to the emerging nature of microplastic pollution, it is not yet clear what the associated human health risks are. Humans can be exposed to microplastics through ingestion, inhalation, and even through dermal contact [45]. Reviews on the effect of microplastic contamination on humans are available; however, the information currently provides no definite conclusions [45–47]. Nevertheless, through investigating the effect that microplastics have on other organisms, linkages for health effects that may occur in humans can be discussed. For example, cytotoxicity may be prompted by microplastic contamination in the human body, as the particles are not membrane bound and could potentially interact with cell structures [48]. This has been illustrated in a study that performed an *in vitro* lab testing on environmentally collected plastic particles which ultimately evoked cytotoxicity [49]. Difficulties researching the human health effects of microplastics exist due to the issues potentially not arising until years after the exposure. It is important to monitor and continue researching in this field as humans are estimated to ingest 39,000–52,000 microplastic particles every year [50].

3.2 Effect of microplastics on fauna

The current literature has a greater focus on the effect of microplastics on aquatic fauna compared to their terrestrial counterpart. This is predominately due to microplastic pollution tending to follow pathways that end up in aquatic environment, hence there is a greater exposure of the contaminant to aquatic fauna [51][]. Table 1 gives a brief overview of studies investigating the toxic effect of microplastics on fauna. It is evident that microplastics can have negative consequences on the physiological and biological processes of a variety of species. For example, microplastics ingested by mice were found to impair skeletal muscle regeneration [62] and when ingested by copepods (crustaceans), a decrease in ingestion rate and swimming speed was reported [4]. Although aquatic fauna has been the focus of the current literature due to the higher probability of exposure, it is still important to research into the toxic effect of microplastics on terrestrial fauna. Research has begun looking into microplastics effect on terrestrial organisms however there are still significant gaps in the literature. Filling these gaps will showcase a holistic understanding of the effects of microplastics on all faunae.

3.3 Effect of microplastics on flora

Microplastics have the ability to enter plant communities through soil mediums [64]. Once microplastics have been adsorbed by a plant, they have the potential to influence the plants biomass, influence the nutrient uptake, impact the growth of the plants roots and leaves, and can also affect germination rates [65–67]. Table 2 briefly outlines recent literature that has investigated the effects that microplastics can have on different plant species. Although all combinations of microplastics and plant species are yet to be studied, the current literature states that in general, the occurrence of microplastics in plants has negative impacts. It is important to continue investigating the impacts that microplastics are having on plant populations as they are a vital key to a sustainable future.

4. Microplastics as a vector for contaminants of concerns

As well as being a significant contaminant of concern, microplastics also have the ability to act as vectors for a wide range of different chemical and biological contaminants [73]. The current literature has highlighted microplastics ability to adsorb chemical contaminants such as pharmaceuticals and personal care products [74], per-fluorinated alkyl substances [75], polyaromatic hydrocarbons [76], polychlorinated biphenyls [77], heavy metals [78], and polybrominated diethers [79]. On top of the chemical contaminants, microplastics also can act as vectors for both bacteria and viruses [80]. Microplastics ability to adsorb pharmaceuticals, especially antibiotics, is a particular focus of the current literature due to the potential links between antibiotic sorption onto microplastics and the development of antibiotic resistant bacteria (ARB) and antibiotic resistance genes (ARGs) [81]. Understanding the mechanisms behind microplastics acting as carriers for contaminants and what factors affect contaminant carrying capacity is important in understanding the implications and impact that this has on the health of humans and our environment.

4.1. Mechanisms of microplastic–contaminant interactions

Current literature states that there are three primary mechanisms that allow microplastics to act as vectors for a variety of contaminants, namely, hydrophobic interactions, electrostatic interactions, and pore filling interactions [74]. Hydrophobic interactions involve two nonpolar substances aggregating caused by the presence of a polar medium such as water. Many polymers (PET, PS, PP, and PE) are naturally hydrophobic materials, allowing hydrophobicity to be a primary driver in microplastics acting as vectors for a range of contaminants [82]. Sorption of antibiotics onto microplastics, particularly PE was found to be heavily influenced by hydrophobic interactions [83–86]. Electrostatic interaction is the process of two molecules being either attracted or repulsed through positive or negatively charged molecules [87,88]. The attraction between oppositely charged

Table 1. Brief snapshot of the recent literature surrounding the toxic effect of microplastics on fauna.

Species	Microplastic	Toxic Effect	Reference
Aquatic-Based Fauna			
Lugworm (Arenicola marina	UPVC	Inhibited energy reserves and feeding activity	[5]
Copepod (Centrop ges typicus)	PS	Decrease in the swimming speed, feeding capacity, and ingestion rate	[4]
Crab (carcinus maenas)	PP fibers	Significant reduction in energy for growth, reduction in food consumption	[52]
Zebrafish (Danio rerio)	PS	Microplastic accumulation was reported in the gills, gut, and liver. Noteworthy changes of hepatic metabolites within the zebrafish.	[53]
Goldfish (Carassius carassius)	EVA, PS, PA	Weight loss, damaged to the buccal cavity as a result of chewing microplastics, inflammatory response	[54]
Jacopever (Sebastes schlegelii)	PS	Microplastic accumulation was reported in the gills, intestine, and liver. Swimming speed and ranged was reduced. Feeding times increased.	[55]
Silver barb (Barbodes gonionotus)	PVC	Microplastic accumulation was noted in the intestine of the fish. Increased trypsin and chymotrypsin was seen to prevent unwanted destruction of cellular proteins.	[56]
Marine mussels (Mytilus galloprovinciallis)	Synthetic microfibres	Damaged gill tissues and damage to organisms DNA	[57]
Clupeidae (Ramnogaster arcuate)	PET, PP	Negatively affected feeding activity	[58]
Terrestrial-Based Fauna			
Common earthworm (Lumbricus terrestris)	PE	Reduction in growth rate.	[59]
Terrestrial worm (Enchytraeus cypticu)	Nylon and PVC	Reduction in reproduction	[60]
Silkworm (Bombyx mori)	PS	Bioaccumulation occurred in the gut tissues. Exposure supressed the immune response.	[61]
Mice (mus musculus)	PS	Developed oxidative stress. Impaired regeneration of skeletal muscle.	[62]
Wistar Rat (Rattus norvegicius)	PS	Death of mitochondria cells. Disrupted the structure and function of the heart.	[63]

*UPVC = Unplasticized polyvinyl chloride, PS = Polystyrene, PP = Polypropylene, EVA = Ethylene-vinyl acetate, PA = Polyamide, PVC = Polyvinyl chloride.

Table 2. Brief snapshot of the recent literature surrounding the toxic effect of microplastics on plants.

Plant Species	Microplastic	Toxic Effect	Reference
Common Duckweed (Spirodela polyrhiza)	PS	Microplastics absorbed to the roots of the plant but did not show any signs of growth impairment.	[68]
Common bladderwort (Utricularia vulgaris)	PS	High levels of ecotoxicity and oxidative damage was reported. Growth rate was also found to been affected by microplastic presence.	[69]
Welsh Onion (Allium fistulosum)	PA, PE, PP, PET	Altered the traits of the leaves and roots.	[70]
English Ryegrass (Lolium perenne)	PLA	Bud length was reduced, and the rate of germination decreased	[71]
Wheat (Triticum aestivum L.)	PS	Increased carbon/nitrogen levels. Reduction in the absorption of micronutrients. Increased root elongation.	[72]
Lettuce (Lactuca sativa L.)	PS	Decreased nutrient accumulation as well as a reduction in plant growth.	[6]
Garden cress (Lepidium sativum L.)	PVC	High doses of PVC seen a reduction in root length, shoot length and gemination rate	[7]

*PET = Polyethylene terephthalate, PS = Polystyrene, PP = Polypropylene, PLA = Polylactic Acid, PA = Polyamide, PVC = Polyvinyl chloride.

molecules gives microplastics the ability to interact with and become a vector for contaminants. This was illustrated through the sorption experiment of negatively charged PE particles, with a negatively charged antibiotic and a positively charged pharmaceutical [85]. Higher sorption rates were found between the microplastics, and the pharmaceuticals compared to the microplastics and the antibiotics. This was due to the electrostatic interactions being favorable for the microplastic and pharmaceutical combination as they were oppositely charged. Pore filling interactions involve the physical process of contaminants becoming encased in the micro or nano pores of microplastics [89,90]. Pore filling interactions can have higher influence on the sorption of contaminants depending on the properties that the polymer exhibits. Due to the structure of glassy polymers (PS, PVC, and PA), pore filling interactions has the highest influence on sorption capacity [91]. Weathered polymers are susceptible to an increased number of pores and cracks on the surface, allowing for more sites for pore filling interactions to occur [92].

The above-mentioned mechanisms are stated to be the three dominant interactions that allow microplastics to act as vectors for contaminants, however, it is noted that secondary interactions do play important roles in this process (Figure 4). Van der Waals interactions and π–π interactions are further mechanisms that are present in the complex interactions that occur when microplastics act as vectors for contaminants, however, these interactions have not been reported as thoroughly in the literature.

4.2. Polymer-specific factors that affect sorption capacity

Polymer type, degree of degradation, and particle size all play critical roles in affecting the sorption capacity of contaminants onto microplastics [93]. The effect of different polymer types affecting sorption capacity was illustrated through the research performed by Guo et al. [94]: the sorption capacity of six different virgin polymers (PS, PE, PVC, PA, PET, PP) and the antibiotic sulfamethazine was investigated. This study found that the sorption capacity of the antibiotic onto the microplastic increased in the following order: PET < PE < PS < PVC < PP < PA. If polymer type played no role in sorption capacity, it would have been expected that all six polymers had the same sorption capacity potential. The differences in sorption capacity between polymers can be attributed to the different chemical structures that each polymer exhibits and the mechanism that influence sorption capacity that was mentioned in Section 4.1. Similar results have been seen for other contaminants within the current literature [84,86,95,96]. Within the current literature that has investigated sorption capacity of antibiotics onto microplastics, it has been found that microplastic degradation significantly increases sorption capacity (Table 3). It is expected that the increase in sorption of antibiotics on degraded microplastics is due to the increase in pores and cracks on the surface of the microplastics, allowing for more locations for antibiotics to be sorbed [95,97]. Although particle size does not

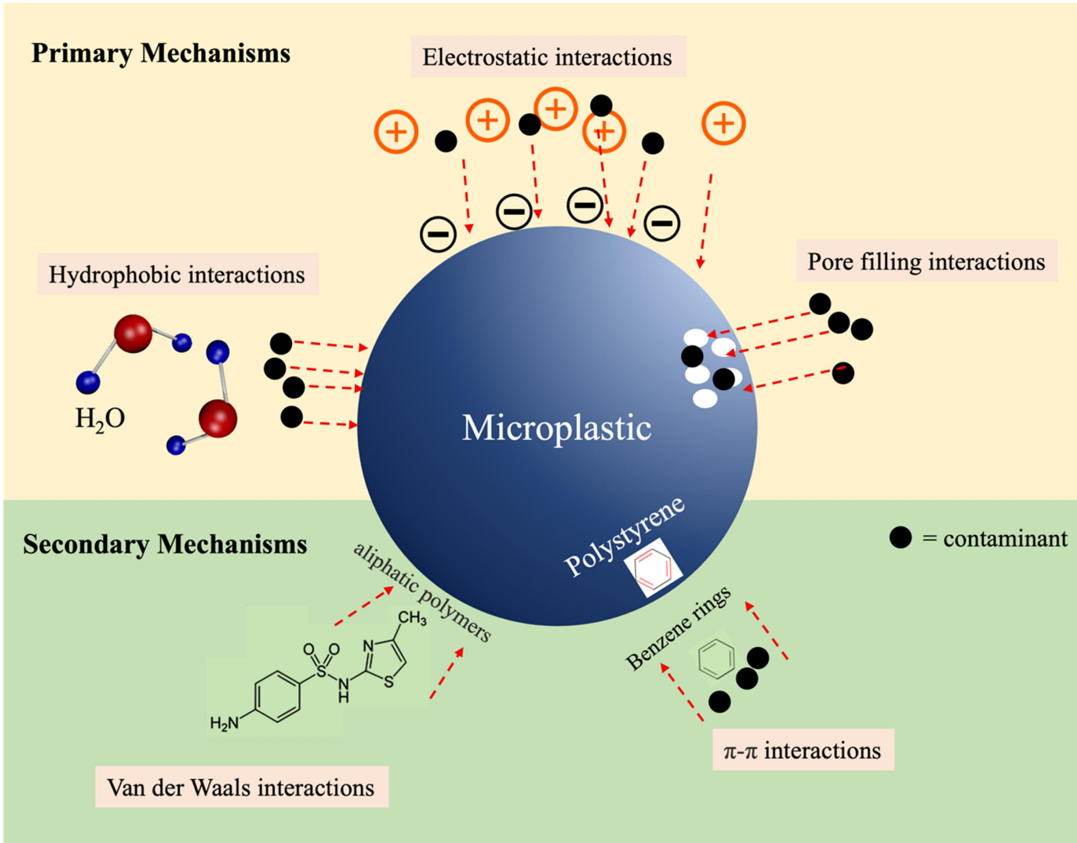

Figure 4. Primary and secondary mechanism that allow microplastics to act as vectors for contaminants.

affect sorption capacity of contaminants as much as other parameters, such as polymer type and surface area, it still plays a role in the sorption kinetics between microplastic and contaminant [88]. Cui et al. [101] investigated the sorption of organic contaminants onto different microplastics and found that although the size did not significantly affect sorption capacity, it did affect equilibrium time. It is clear that there are polymer-specific factors that can either increase or

Table 3. Investigation of the effect of microplastics degradation on antibiotic sorption (adapted from [93]).

Antibiotic	Microplastics Type	Antibiotic Concentration (mg/L)	Method of degradation	% increase or decrease in antibiotic sorption due to aging	Reference
Amoxicillin	TWP PE	0.5–8	Heat activated potassium persulfate aging process (15 days)	24% increase 67% increase	[97]
Ciprofloxacin	PS PVC	2–25	UVC treated (4 × 15W bulbs) for 96 hours and shaken every 24 hours	123.3% increase 20.4% increase	[98]
Ciprofloxacin	PLA PVC	5	UVA treated by 50W/m^2 lamp for 72 hours	34% increase 20.6% increase	[95]
Chlortetracycline	TWP PE	0.5–8	Heat activated potassium persulfate aging process (15 days)	154% increase 130% increase	[97]
Oxytetracycline	TPU	2.5–40	UV treated by 5 mW/cm^2 lamp for 10 days, shaken every 12 hours	87.5% increase	[99]
Oxytetracycline	PS	2–50	PS foam found on beaches in China (age unknown)	110% increase	[92]
Oxytetracycline	PLA	0–12	Microbial degradation	39% increase	[100]
Tetracycline	PLA PVC	5	UVA treated by 50W/m^2 lamp for 72 hours	171% increase 133% increase	[95]

*PET = Polyethylene terephthalate, PS = Polystyrene, PE = Polyethylene, PLA = Polylactic Acid, TWP = Tyre Wear Particles, PVC = Polyvinyl chloride.

decrease the sorption capacity of contaminants onto microplastics, and it is never just one factor that has influence over the reaction. The combinations the polymer properties, the media that the reaction is taken place in and the contaminant properties all play a dynamic and complex roles when trying to understand the sorption capacity potential [93].

4.3. Implications of microplastics acting as vectors for contaminants

When organisms are exposed to microplastics there is the potential that the contaminants attached to the microplastics can spread to the host organism. The transfer of polycyclic aromatic hydrocarbons (PAH) and heavy metals from microplastics to an exposed organism has been documented in recent literature. Stollberg et al. [8] investigated the toxic effect that microplastics contaminated with fluoranthene had on blue mussels. The study illustrated the blue mussels that were exposed to the contaminated microplastics had greater levels of the PAH in its tissues when compared to the control sample, indicating the transfer of fluoranthene from the microplastic to the host organism. The increased toxic effect of contaminated microplastics has also been illustrated when heavy metals was the studied pollutant. Tunali et al. [102] demonstrated that when microalgae was exposed to PS contaminated with magnesium, copper, and zinc, its growth was inhibited. Zhang et al. [103] investigated the toxic effects of PS contaminated with cadmium on zebrafish and discovered the embryo development was significantly affected. Limited studies are currently available on the effects of microplastics that are contaminated with antibiotics on organisms [93], but it is suggested that when the combination of the two pollutants are ingested by aquatic organisms, it would have a greater effect on the health of the organism than if the organism was exposed to each pollutant individually [43].

Another consequence of antibiotic sorption onto microplastics is the possibility of the formation of ARB and ARGs on the surface of microplastics. This is due to the microplastic having the ability to host both bacterial communities and antibiotics [104]. Biofilms containing a high concentration of microbial cells can form on the surface of microplastics [105]. The long exposure of these bacterial communities to antibiotics increase the chance for some microbial cells to develop a resistance to the antibiotic [106]. Bacteria that are then resistant to the antibiotic survives and multiplies, eventually creating a bacterial community that now has a high antibiotic resistance. Microplastics have been found to have the capacity to be vectors for ARGs in landfill leachate, in sewage, in aquatic environments and in terrestrial environments [107–111]. The same pathways that microplastics enter the environment through are shared commonly with antibiotics, allowing for the occurrence and potential generation of ARB and ARGs to become more common. Further implications around microplastics acting as vectors for contaminants arise when trophic transport of the pollutant through food chains occur. A potential source for microplastics in human beings is thought to be through the food chain [44]. With microplastics acting as vectors for a range of contaminants, there is the potential that they will bioaccumulate through the food chain and spread their toxicity across all organisms involved (Figure 5) [112].

5. Future perspectives

This article provides a brief overview of the current literature on the sources and implications of microplastics being an emerging contaminant. Future research areas that will have a high impact should focus on:

- Further investigation of emerging microplastic sources. To understand microplastic as a contaminant in the environment as a whole, first we need to understand where the sources for microplastic pollution is coming from. Once sources have been located, remediation strategies can be applied to limit the environmental loading of microplastics.
- Further evaluation of the toxic effect of microplastics on terrestrial fauna. As stated in this review, most of the fauna that has been studied has been marine based. Investigating the toxicity of the pollutant on land-based

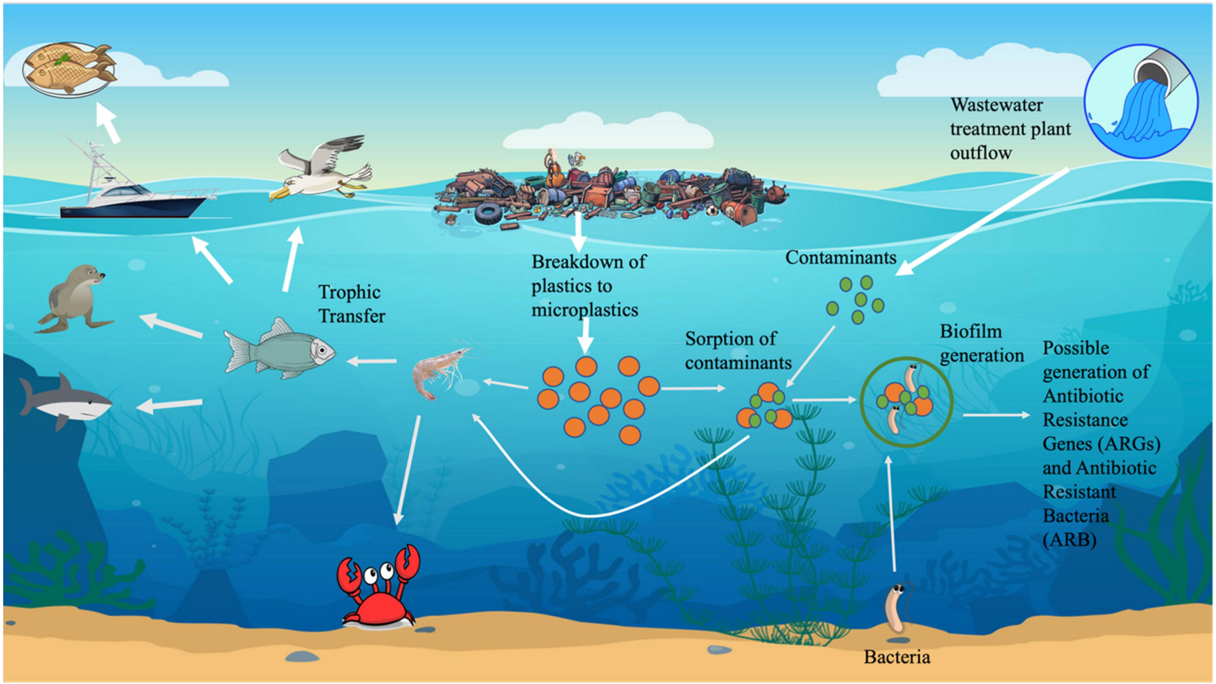

Figure 5. Trophic transfer of microplastics and contaminants through the food chain (adapted from [93].

mammal will create a further understanding of the effects that microplastics may have on humans.

- Further research into the formation and occurrence of ARB and ARGs on microplastic pollution. A lot of strain has been put on the health system after the COVID-19 global pandemic. Antibiotic resistance is an area that will have a potentially deadly consequence on the way the health system operates. Understanding how ARB and ARGs are formed is critically important, and since microplastic may be a hotspot for this, it is a significantly important research area.

6. Conclusions

This overview paper discussed the implications of microplastics being an emerging contaminant of concern. As well as being a contaminant of concern in itself, microplastics also have the ability to act as vectors for other contaminants. The ability of microplastics to host both antibiotics and bacterial communities on the same surface, leads to the possibility of microplastics being vectors for ARB and ARGs. Many gaps in the literature are still present, and with the significant abundance of the pollutant in the environment, it is best that research focuses on all aspects surrounding microplastics to greater our understanding.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research has been carried out with the support of the Australian Government Research Training Program Scholarship to Michael Stapleton, through University of Wollongong.

Data availability statement

This was a meta-analysis of the data from articles available in the open literature.

Author contribution statement

Michael J. Stapleton Conceptualization, Investigation, Writing – original draft.

Faisal I. Hai: Conceptualization, Supervision, Writing – Reviewing and Editing.

All authors agree to be accountable for all aspects of the work. All authors confirm that they meet the criteria for authorship as per the ICMJE criteria.

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